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Thermal performance of pouch Lithium-ion battery module cooled by phase change materials

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Abstract

Battery thermal management is of great significance for increasing the thermal safety and prolonging the service life of the electric vehicle battery pack. In this paper, the thermal property of pouch Lithium-ion battery module cooled by PCMs (Phase Change Materials) was investigated. The three-dimensional thermal models of battery modules consisted of different thickness batteries were established to study the effects of space between adjacent batteries, melting point and thermal conductivity of PCMs on cooling performance. The results showed that the T_{max} (maximum temperature) and ΔT_{max} (maximum temperature difference) declined when space between modules and thermal conductivity of PCMs increased. And the decline became more obviously with the increasing melting point of PCMs. T_{max} increased and ΔT_{max} declined as the melting point of PCMs increased. On the basis of the T_{max} of battery module meeting the temperature requirements, improving the space between adjacent batteries, melting point and thermal conductivity of PCM properly contributed to enhance the conformity of temperature filed. The conclusion would contribute to the design of battery thermal management system based on PCMs.

Keywords: Battery thermal management; Phase change materials; Melting point; Thermal conductivity

Nomenclature			
t	time (s)	h	heat transfer coefficient ($W\cdot m^{-2}\cdot K^{-1}$)
		λ	thermal conductivity ($W\cdot m^{-1}\cdot K^{-1}$)

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T	temperature (K)	θ	thickness (mm)
T_{max}	maximum temperature (K)	E	Voltage (V)
T_{min}	minimum temperature (K)	R	resistance (Ω)
ΔT_{max}	maximum temperature difference (K)	**Subscripts**	
T_0	ambient temperature (K)	c	cell
c_p	specific heat ($J\cdot kg^{-1}\cdot K^{-1}$)	m	melting point
ρ	density ($kg\cdot m^{-1}$)	**Acronyms**	
q	heat (J)	PCMs	phase change materials
I	current (A)		

1. Introduction

Lithium-ion batteries made from multiple cells connected in series and parallel have been extensively used in hybrid electric vehicle and electric vehicle due to their high power capability and energy density compared with other secondary battery chemistries. However, there are some thermal limitations in the application of lithium batteries currently: thermal runaway, non-uniform temperature, and poor low-temperature performance. Additionally, the thermal safety risk of large capacity lithium battery module is improved as vast heat can be released during a single cell failure [1]. The battery thermal management system is used to limit T_{max} of battery module and decrease ΔT_{max} to prolong the battery lifespan [2]. Many battery thermal management technologies have been developed in the past few decades, including air cooling, liquid cooling, phase change materials (PCMs) cooling and some multiple cooling methods [3-4].

As the pump or blower is not required, passive thermal management based on the PCMs is more cost-effective. The heat generated by the battery can be absorbed by the PCMs close to the cell in battery module. When the temperature of the cell reaches the PCMs' melting point, the further heat will be stored in the form of latent heat and the temperature stop increasing. The effect of PCMs on square lithium-ion battery was investigated and the results indicated that PCM could improve the uniformity of temperature distribution and keep battery in safe temperature range [5]. Because of the relatively low thermal conductivity ($< 0.5\ W\cdot m^{-1}\cdot K^{-1}$), there is large temperature gradient inside the paraffin during the heat transfer. Different measures were used to improve the thermal conductivity of PCM as it following: adding thermal conductive additives, such as carbon-fiber chips, metal powder or carbon nanotube into PCMs [6]; absorbing PCMs with metal foam or expanded graphite to form composites [7]; using metal frame or fins [8-9]. As the thermal conductivity increases at the cost of decreasing latent heat, the appropriate ratio of thermal conductivity between PCMs and battery is necessary in order to achieve a good cooling performance and decrease the mass and volume.

For pouch Lithium-ion battery with different thickness, selecting the appropriate spacing, melting point of PCMs and thermal conductivity to restrain the T_{max} of battery less than 45 ℃ and make the ΔT_{max} less than 5 ℃ was the key point in the design of battery thermal management based on PCMs. In this paper, we investigated the cooling performance of PCMs used on the pouch Lithium-ion battery module. The study focused on the performance of battery thermal management based on PCMs through simulation. The three-dimensional thermal models of battery modules consisted of different thickness batteries cooled by PCMs was built. The influence of spacing between adjacent batteries on cooling performance was investigated. And the effect of PCMs melting point and thermal conductivity, as well as the thermal conductivity of battery, on temperature field of battery module was studied.

2. Structure

2.1. Physical problem

The battery module consisted of 24 parallel pouch cells. Several cells made up battery. When each battery consisted of 1, 2, 3 and 4 single cells, the thickness of battery was 7mm, 14mm, 21mm and 28mm, respectively. The PCMs was filled into the gaps between the adjacent batteries. The PCMs surrounded the batteries and reduced the T_{max} and the ΔT_{max} of the battery during the discharge. The schematic of the different module was shown in Fig. 1.

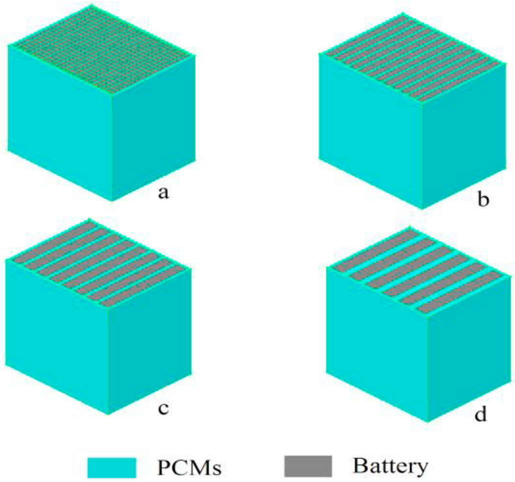


Fig. 1 The structure of battery module cooled by PCMs: (a) each battery consisted of 1single cell, (b) each battery consisted of 2 single cells, (c) each battery consisted of 3 single cells, (d) each battery consisted of 4 single cells

The physical sizes and thermal properties used in the simulation are summarized in Table 1.

Table 1 Specifications and parameters of the cell

Parameters	Value	Parameters	Value
Nominal capacity (Ah)	20	Electrolyte	$LiPF_6$
Nominal voltage (V)	3.25	Cu foil thickness (mm)	0.01
Size (mm)	230×170×7	Al foil thickness (mm)	0.02
Weight (g)	545	Anode thickness (mm)	0.08
Maximum discharge current (A)	40	Cathode thickness (mm)	0.07
Discharge operating temperature (K)	253-333	Separator thickness (mm)	0.03
Anode material	$LiPFeO_4$	Thermal conductivity along surfaces (W m^{-1} K^{-1})	12
Cathode material	Li_xC_6	Thermal conductivity in thickness direction (W $m^{-1}K^{-1}$)	0.34
Separator	PE/PP/PP	Average cell specific heat (J kg^{-1} K^{-1})	2138

Gambit was used to mesh the model and FLUENT 15 was used as the simulation software. The theoretical model is developed based on the assumptions: the PCMs' density and thermal conductivity was constant.

In order to simplify the cost of calculation, the theoretical model was developed based on the following assumptions:

(1) The specific heat of PCMs in liquid and solid phase was constant.
(2) The volume of the PCMs was constant during the phase change process.
(4) The PCS was assumed to be incompressible.

2.2. Governing equations

The energy conservation equation of cell and PCMs can be expressed as:

$$\frac{\partial}{\partial t}(\rho_c c_{pc} T_c) = \lambda_c \nabla^2 T_c + q_c \tag{1}$$

$$\frac{\partial}{\partial t}(\rho_{PCMs} c_{pPCMs} T_{PCMs}) = \lambda_{PCMs} \nabla^2 T_{PCMs} + q_{PCMs} \tag{2}$$

The heat generation q_c within the Li-ion battery during discharge can be expressed as:

$$q_c = I^2 R - I T_c \frac{dE}{dT_c} \tag{3}$$

According to Newton's law of cooling, the boundary equations in each direction can be expressed as follows:

$$
\begin{aligned}
-\lambda \frac{\partial T}{\partial x} &= h(T - T_0), \quad x = 0, X \\
-\lambda \frac{\partial T}{\partial y} &= h(T - T_0), \quad y = 0, Y \\
-\lambda \frac{\partial T}{\partial z} &= h(T - T_0), \quad z = 0, Z
\end{aligned}
\tag{4}
$$

Where T_0 was set as 298 K in the simulation and the value of h was 3 [4].

The independent test of grid number and time step were performed to guarantee accuracy. As showed in Fig.2, the total heat transfer rate of a certain model varied with the increasing grids number. When the grids number was 213000 and 354000, the difference of total heat transfer rate was less than 0.1%. Balancing the simulation precision and time, the mesh with 213000 grids and a time step of 0.1 s were used in the simulation. The convergence criteria for this study were chosen to be 10^{-4} and 10^{-6} for flow and energy, respectively.

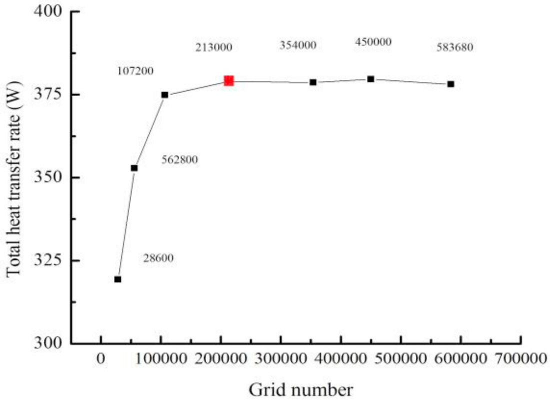
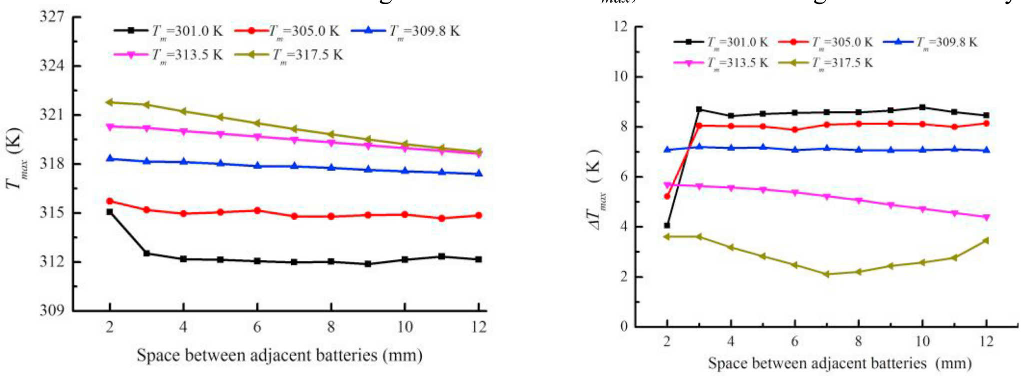


Fig. 2 Mesh independent solution analysis

3. Results and discussion

3.1. Effects of space between adjacent batteries

The spacing between adjacent batteries determined the amounts of PCMs filled between the batteries. Large battery spacing would increase the module volume and decrease the energy density of module. Small battery spacing filled with small amount of PCMs might not restrain the T_{max}, as the PCMs might melt absolutely.

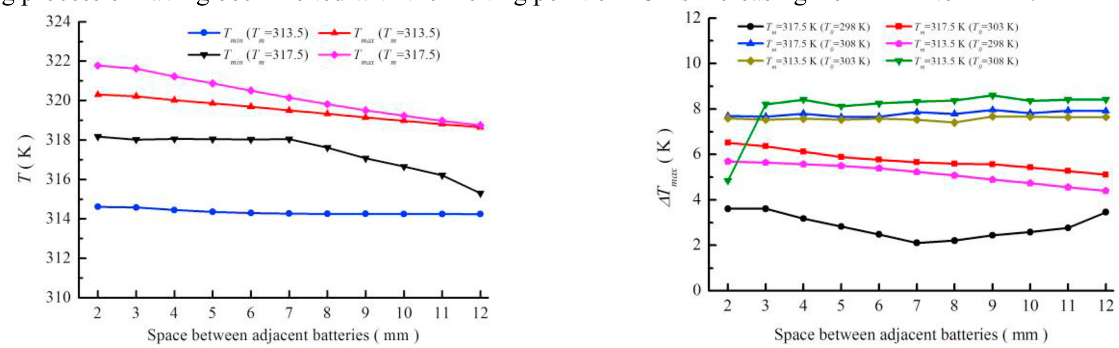


(a) (b)

Fig. 3 The T_{max} (a) and ΔT_{max} (b) of battery module temperature versus space between adjacent batteries

In this section, each battery in the module consisted of 2 cells to research the effects of space between adjacent batteries. The battery spacing increased from 2 mm to 12 mm and the melting point was in the range of 301 K and 317.5 K. The simulation results showed that the increasing battery spacing led to the module T_{max} decreasing gradually. And the downtrend enlarged with the increasing PCMs' melting point, as it was shown in Fig.3 (a). As the melting point of PCMs was 317.5 K, the T_{max} decreased by 3 K with the battery spacing increasing from 2 mm to 12 mm. When the melting point of PCMs was less than 305 K and the battery spacing was 2mm, there was not enough PCMs with latent heat in the module. As a result, the PCMs would lose the ability of restrain battery T_{max} after having melted absolutely during the battery discharging process. When the battery spacing was more than 3 mm, the battery cooling performance was improved and the T_{max} decreased by 2.5 K, because of enough PCMs always having the ability of absorbing heat in the form of latent heat during the discharging process. With the spacing increasing continuously, the T_{max} varied slightly.

The Fig.3 (b) showed that module ΔT_{max} presented downtrend on the whole as the battery spacing increased gradually. And the trend enlarged with the increasing PCMs' melting point. When the melting point of PCMs was less than 305 K, the ΔT_{max} increased sharply with the battery spacing increasing from 2 mm to 3 mm. Because of all the PCMs in the module having melted absolutely, heat generated by batteries was absorbed by PCMs in the form of sensible heat. The battery temperature increased quickly and the difference between module T_{max} and T_{min} was decreased. With the spacing increasing continuously, the ΔT_{max} varied slightly. In the Fig.2 (b), it showed that when the melting point of PCMs was 317.5 K, the ΔT_{max} increased with increasing battery spacing then decreased. ΔT_{max} was lowest when the battery spacing was 7 mm. It resulted from the reason that the temperature of battery part far away the module center was lower than melting point and the temperature difference was enlarged, as battery spacing exceeded 7 mm. When the melting point of PCMs was 313.5 K, all the PCMs in the module was in the melting process or having been melted with the melting point of PCMs increasing from 2mm to 12mm.



(a) (b)

Fig. 4 (a) module T_{max} and T_{min}, (b) module ΔT_{max} in different T_0 versus different space between adjacent batteries:

The T_{min} of module changed slightly at the end of battery discharging process. As the T_{max} decreased with increasing melting point of PCMs, the ΔT_{max} of the module decreased continuously. This was shown in the Fig.2 (c). The Fig.4 (b) showed the variation of module ΔT_{max} versus battery space in different T_0. When the T_0 was unchanged, the variation of ΔT_{max} in Fig.4 (b) was similar to that in Fig.3 (b). As the T_0 increased, the module ΔT_{max} increased. When the battery spacing was 2 mm, melting point of PCMs was 313.5 K and the T_0 was 308 K, the module ΔT_{max} was small, because of the all the PCMs in module having been melted at the end of battery discharging process.

3.2. Effects of PCMs' melting point

Melting point was one of the key parameters in the design of battery thermal management based on PCMs. PCMs with high melting point might have not melted after the discharging process. It led to the high T_{max}. When the ambient temperature increased, the PCMs with low melting point might have melted and could not absorb the heat generated by battery in the form of latent heat. This led to the T_{max} increase continuously during the discharging process. In this section we choose the C_{18}, C_{19}, C_{20}, C_{21} and C_{22} as the PCMs used in the battery cooling, as their melting point located in the working temperature range of lithium-ion battery. The thermodynamic parameters of different PCMs were shown in Table 2.

Table 2 Properties of PCMs used in the simulation

PCMs	Melting point (K)	Latent heat of fusion ($kj \cdot kg^{-1}$)	Density ($kg \cdot m^{-3}$)	Heat conductivity coefficient (W•m-1•K-1)
C_{18}	301	243	778	0.151
C_{19}	305	245	778	0.151
C_{20}	309.8	247	778	0.151
C_{21}	313.5	248	779	0.151
C_{22}	317.5	249	780	0.151

The Fig.5 showed that T_{max} of battery module increased with the PCMs' melting point. The small ΔT between cell surface and PCMs caused by increasing melting point would impede the heat transfer. As the battery thickness decreasing, the uptrend of T_{max} was more obvious. The T_{max} of battery with 28mm thickness increased by 3 K with the melting point increasing from 301 K to 317.5 K. As the thickness of battery was 7 mm, the increasing was only 14.2 K. The T_{max} of thinner battery generating less heat was more easily influenced by the heat transfer. In order to restrain the T_{max}, thin battery should be cooled by low melting point PCMs.

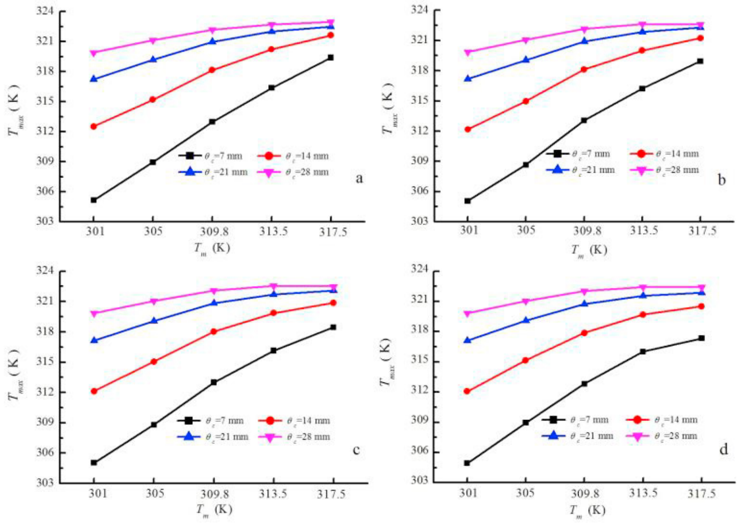


Fig. 5 T_{max} of module with different battery thickness versus T_m: (a) batteries spacing 3 mm, (b) batteries spacing 4 mm, (c) batteries spacing 5 mm, (d) batteries spacing 6 mm

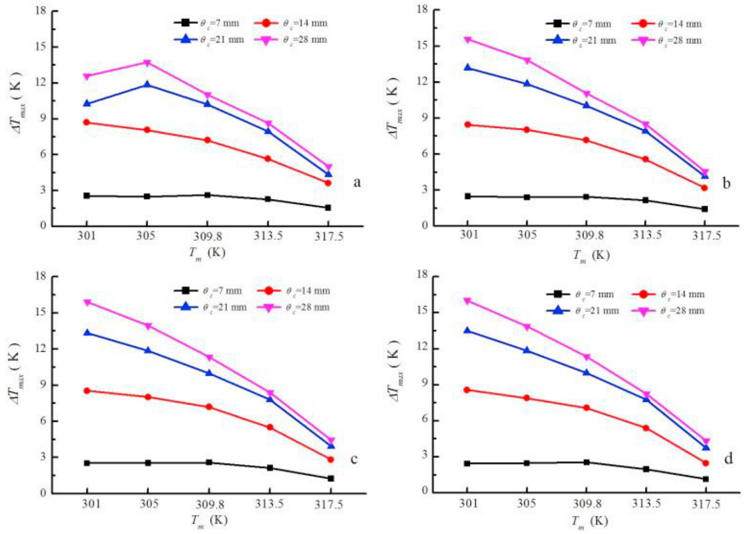


Fig. 6 ΔT_{max} of module with different battery thickness versus T_m: (a) batteries spacing 3 mm, (b) batteries spacing 4 mm, (c) batteries spacing 5 mm, (d) batteries spacing 6 mm

ΔT_{max} of battery module decreased with the PCMs' melting point as it was shown in Fig.6. As the battery thickness increased, the downtrend of ΔT_{max} become more obvious. In the Fig.6(a), ΔT_{max} of battery module with small battery spacing and big thickness battery increased and then decreased as the melting point increased. The PCMs with low melting point melted completely after absorbing the heat. It led to the higher minimum temperature of battery module and decreased the ΔT_{max}. As the battery spacing and the amount of PCMs increased, the phenomena disappeared.

3.3. Effects of PCMs' thermal conductivity

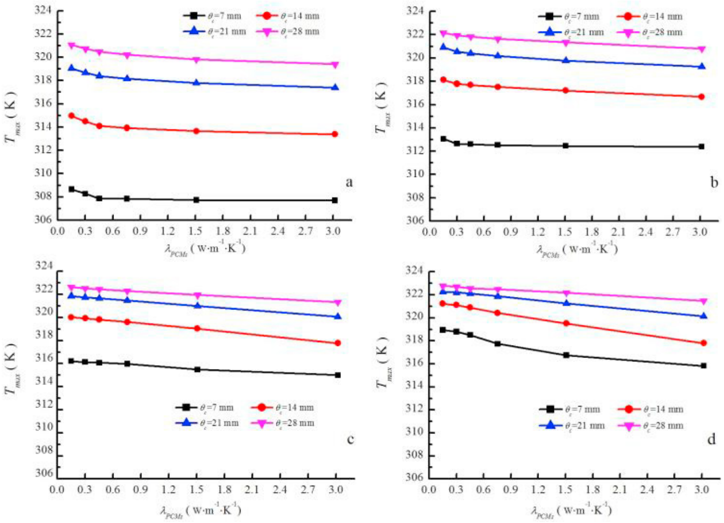


Fig. 7 T_{max} of module with different battery thickness versus λ_{PCMs}: (a) T_m = 305 K, (b) T_m= 309.8 K, (c) T_m= 313.5 K, (d) T_m= 317.5 K

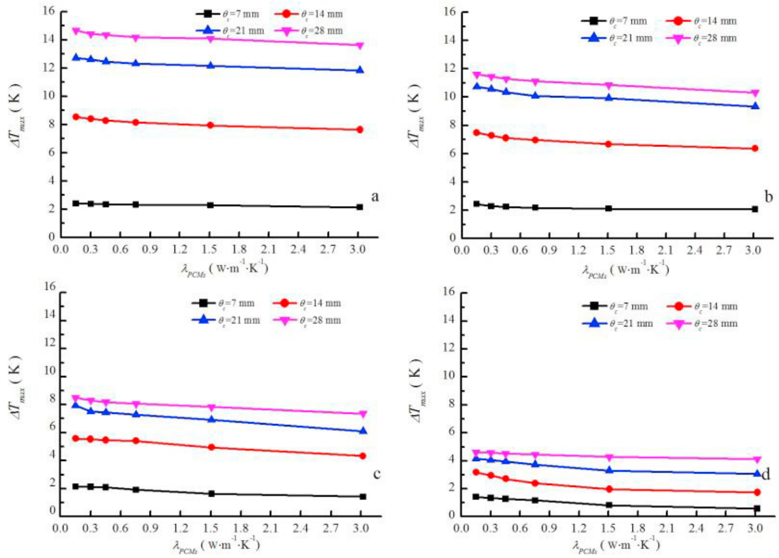


Fig. 6 ΔT_{max} of module with different battery thickness versus λ_{PCMs}: (a) T_m = 305 K, (b) T_m= 309.8 K, (c) T_m= 313.5 K, (d) T_m= 317.5 K

Paraffin are difficult to employ efficiently because of the thermal conductivity being lower than 0.5 $W \cdot m^{-1} \cdot K^{-1}$. High thermal conductivity of PCMs shortened the time of heat conduct from the battery surface to PCMs interior. In order to decrease the temperature gradient in paraffin, operation of improving λ_{PCMs} was at the cost of decreasing latent heat. Appropriate thermal conductivity was one of important parameters in design of battery thermal management based on PCMs. In this section, the effect of λ_{PCMs} on battery temperature was studied.

The Fig.7 and Fig.8 showed the effect of λ_{PCMs} on T_{max} and ΔT_{max} of battery module. It was clear that the variation trend of T_{max} and ΔT_{max} were both declined gradually as λ_{PCMs} increased. As thickness of battery increased, the effect of λ_{PCMs} on T_{max} was increased. On the contrary, the effect of λ_{PCMs} on ΔT_{max} was decreased as thickness of battery increased. As the melting point increased, the effect of λ_{PCMs} on T_{max} and ΔT_{max} increased obviously. Comparing the 4 figures in Fig.5, it showed that if the melting point of PCMs was lower the downtrend of T_{max} was obvious in the progress of λ_{PCMs} increasing by 2-5 times. If the melting point of PCMs was 317.5K, the downtrend of T_{max} was obvious in the progress of λ_{PCMs} increasing by 5-10 times. If the λ_{PCMs} increased continuously, the temperature changed slightly because of the main thermal resistance caused by battery's low thermal conductivity. As a result, there was no need to increase the λ continuously at the cost of decreasing the PCMs' latent heat. What's more, it might increase the module's weight and decrease the energy density.

4. Conclusions

In this paper, the thermal property of battery thermal management based on PCMs was investigated with numerical simulation method. And the thermal models of battery modules consisted of different thickness batteries were established. The study focuses on the effects of space between adjacent batteries, melting point and thermal conductivity of PCMs on cooling performance.The main results included:

(1) The T_{max} and ΔT_{max} declined when space between modules and thermal conductivity of PCMs increased. And the decline became more obviously with the increasing melting point of PCMs.
(2) The T_{max} increased and ΔT_{max} declined as the melting point of PCM increased. Increasing the thermal conductivity of the PCMs and cell could restrain the T_{max} and ΔT_{max}.
(3) On the basis of the T_{max} of battery module meeting the temperature requirements, improving the space between adjacent batteries, melting point and thermal conductivity of PCM properly contributed to enhance the conformity of temperature filed.

5. Acknowledge

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References

[1] T. Bandhauer, S. Garimella and T. Fuller, Electrochemical-Thermal Modeling to Evaluate Battery Thermal Management Strategies II. Edge and Internal Cooling, J. Electrochem. Soc. 162 (1) A125-A136 (2015).
[2] L Zhou, Y Zheng, M Ouyang, L Lu, A study on parameter variation effects on battery packs for electric vehicles, J. Power Sources 364 (2017) 242-252.
[3] Z. An, L. Jia, Y. Ding, C. Dang, X. Li, A Review on Lithium-ion Power Battery Thermal Management Technologies and Thermal Safety, Appl. Therm. Eng. 123 (2017) 929–939.
[4] F. Bai, M. Chen, W. Song, Z. Feng, Y. Li, Y. Ding, Thermal management performances of PCM/water cooling-plate using for lithium-ion battery module based on non-uniform internal heat source, Appl. Therm. Eng. 126 (2017) 17–27.
[5] N. Javani, I. Dincer, G. Naterer, G Rohrauer, Modeling of passive thermal management for electric vehicle battery packs with PCM between cells, Appl. Therm. Eng. 73 (2014) 307–316.
[6] E. Mettawee, G. Assassa, Thermal conductivity enhancement in a latent heat storage system, Sol. Energy. 81 (2007) 839–845
[7] L. Alva, J. Gonzalez, N. Dukhan, Initial analysis of PCM integrated solar collectors, J Sol Energ. 128 (2006) 173–179
[8] W. Libeer, F. Ramos, C. Newton, M. Alipanahrostami, C. Depcik, X. Li, Two-phase heat and mass transfer of phase change materials in thermal management systems, Int J Heat Mass Tran. 100 (2016) 215–223.
[9] Z. Wang, H. Zhang, X. Xia, Experimental investigation on the thermal behavior of cylindrical battery with composite paraffin and fin structure. Int J Heat Mass Tran. 109 (2017) 958–970.
[10] W. Song, F. Bai, M. Chen, S. Lin, Z. Feng, Y. Li, Thermal management of standby battery for outdoor base station based on the semiconductor thermoelectric device and phase change materials, Appl. Therm. Eng. 137 (2018) 203-217.